UNDERSTANDING GAS MIGRATION IN UNSATURATED FRACTURED POROUS MEDIA USING FIELD EXPERIMENTS AND NUMERICAL SIMULATIONS

S. GUILLON[1,2*], E. PILI[1,2], J-C. SABROUX[3], T.M. VU[4], P.M. ADLER[4]

[1]CEA, DAM, DIF, F-91297 Arpajon, France
[2]Institut de Physique du Globe de Paris, 1 rue Jussieu, F-75005 Paris, France, sguillon@ipgp.fr (* presenting author)
[3]Institut de Radioprotection et de Sûreté Nucléaire, Centre de Saclay, F-91192 Gif-sur-Yvette Cedex, France
[4]UPMC Sisyphe. Boîte 105, 4 place Jussieu, F-75252 Paris Cedex 05, France

ABSTRACT

Understanding the transfer mechanisms of gases in unsaturated fractured rocks is essential for the safety of CO_2 sequestration projects and many other applications. In order to develop our understanding and our modeling capacities, we recently compared field experiments with numerical simulations using several codes, including TOUGH2.

At the Roselend Natural Laboratory underground research facility in the French Alps, a tunnel provides access to the center of an unsaturated fractured crystalline rock formation at 55 m below ground surface. This underground research facility enables the study of gas transfer between a 60 m^3 chamber, isolated at the dead-end of the tunnel, and the surface. Pneumatic injection tests are conducted in the chamber.

We conducted numerical simulations to understand flow and transport processes during the field experiments, taking into account the actual boundary conditions and 3D geometry of the tunnel and chamber. Simulations with air flow (single-phase) reproduce the experimental data and yield values of permeability and porosity that compare well with previous estimates made from hydrogeological tracer experiments and stereological determinations. Simulations with an equivalent homogeneous medium satisfactorily model flow in the pneumatic injection tests. Two-phase flow and tracer transport simulations with TOUGH2 /EOS7R help to investigate the influence of water saturation on gas migration in the unsaturated zone.

INTRODUCTION

The Roselend Natural Laboratory is dedicated to the study of water and gas migration at the field scale under natural conditions. Here, joint experimental and numerical approaches are used to help our understanding of gas flow and transport in the unsaturated zone, at a 50 m scale. Pneumatic injection tests are conducted and numerical simulations of gas flow (single-phase) in a porous medium are performed to estimate both the permeability and the porosity. Gas tracer experiments were carried out using SF_6, noble gases and CO_2. Preliminary simulations of two-phase flow and SF_6 transport in the unsaturated fractured medium using the TOUGH2 code give insights into the influence of water flow on gas migration. The simulations also confirm which parameters and computational features that are necessary for simulating the processes with TOUGH2 in this context.

THE ROSELEND NATURAL LABORATORY

The Roselend Natural Laboratory, in the Western Alps (Provost et al., 2004), is composed of a dead-end horizontal tunnel at an altitude of 1576 m, located below an abandoned quarry (Figure 1). The tunnel is 128 m long and ~ 2.4 m in diameter. It is hosted in fractured gneiss and micaschists, and capped by the same rocks with an increasing thickness of 7 m at the entrance to 55 m at its closed end. The tunnel is located nearby the artificial Roselend Lake at slightly higher elevation than the lake. Head measurements at two piezometers located between the tunnel and the lake indicate that the water table level is ~20 m below the tunnel.

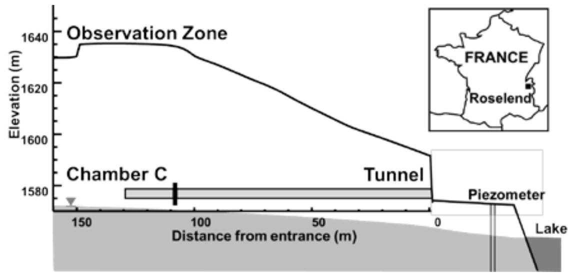

Figure 1. The Roselend Natural Laboratory, with the isolated Chamber C at the end of the tunnel, used for gas tracer injections observed at the surface.

At the end of the tunnel, a chamber (whose length and volume are 20 m and 60 m^3, respectively) is isolated by a wall and a door designed to be air-tight (Figure 1). It is referred to as Chamber C.

EXPERIMENTAL METHODS

Similarly to the work done by Wassermann et al. (2011) to determine the extent of the Excavation Damaged Zone in the Roselend tunnel, we recently conducted pneumatic injection tests in Chamber C (Guillon et al., in prep). Following air injection, a constant overpressure of ca. 200 mbar was reached and maintained for a 100 h period (Figure 2). The injection was then stopped, and the pressure decrease was monitored. Such pneumatic injection tests were repeated several times, under various water saturations.

A gas tracer test with SF_6 was carried out by first injecting the tracer in Chamber C to reach the target concentration, and then injecting fresh air to reach the target 200 mbar overpressure.

NUMERICAL SIMULATIONS

3D numerical simulations of single-phase air flow were conducted in a homogeneous porous medium, using a finite difference code developed at Paris 6 University (Vu, 2012). Water was considered immobile, and water saturation was taken into account by reduction of the apparent porosity and/or permeability. The real 3D geometry of the Roselend site was also taken into account. This numerical model was used to interpret pneumatic injection tests (Guillon et al., in prep). Permeability was estimated from the pressure and flow rate at steady state, while the porosity is obtained by fitting the calculated and experimental pressure decrease (Figure 2).

In the present study, two-dimensional numerical simulations in a homogeneous porous medium were conducted using TOUGH2/EOS7R (water, radionuclide 1, air), in order to investigate the influence of water saturation on gas flow in the unsaturated zone. Simulations were carried out in a 2D vertical cross section perpendicular to the Chamber C axis. Here we consider SF_6 as the gaseous tracer, with a negligible solubility and a diffusion coefficient in air of 10^{-5} m²/s. The initial concentration of SF_6 in Chamber C was set at 1000 ppm, and a constant injection of air (without tracer) was imposed in the chamber, with a 24 L/min flow rate, identical to the experimental determination (Figure 2).

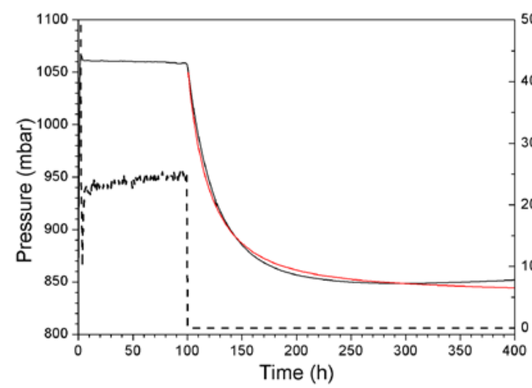

Figure 2. Pressure variation (black solid) and air injection flow-rate (dashed) measured during a pneumatic injection test in Chamber C. The pressure decrease after the end of the injection is reproduced by numerical simulation (red), using the permeability deduced from the steady-state phase of the experiment (Guillon et al., in prep).

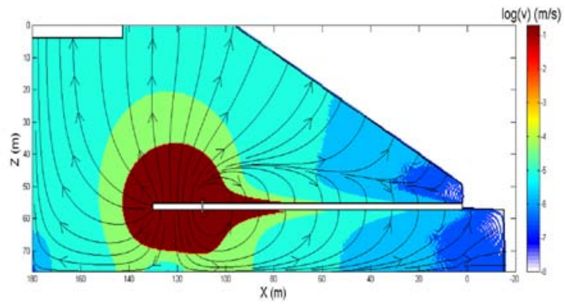

Figure 3. Air velocity and streamlines at steady-state during air injection at 200 mbar overpressure in Chamber C, obtained from 3D numerical simulation of single-phase air flow (modified from Vu, 2012).

RESULTS AND DISCUSSION

Permeability and Porosity in Chamber C

From the repeated pneumatic injection tests, the computed permeabilities and porosities estimated in Chamber C are within a narrow range, from 5×10^{-15} to 8×10^{-15} m² and 4.5% to 4.7%, respectively. Permeability was 1 to 2 orders of magnitude smaller than that obtained for the fully saturated medium by Patriarche et al. (2007) from stereological analysis.

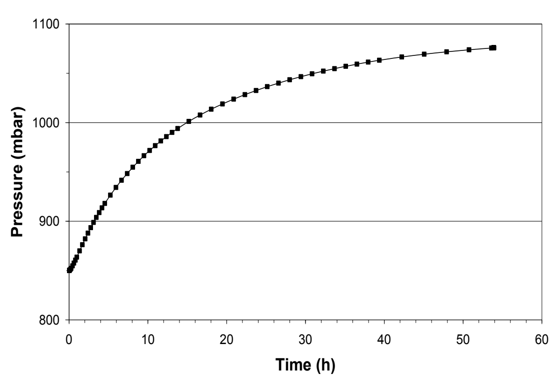

Figure 4. Pressure in Chamber C during air injection at a constant flow-rate of 24 L/min, obtained from numerical simulation with TOUGH2/EOS7R.

Figure 3 shows the steady-state air velocity field and the corresponding streamlines around the tunnel during a pneumatic injection test with an overpressure of 200 mbar in Chamber C. Twenty meters away from Chamber C, air velocity drops and becomes very small. Air injected into the chamber flows towards the atmosphere, but also around the air-tight wall into the tunnel.

The pressure evolution in Chamber C obtained from numerical simulation with TOUGH2 is shown in Figure 4. The values of permeability and porosity necessary to obtain a steady-state pressure in Chamber C consistent with experimental data (Figure 2) are 3×10^{-14} m² and 1% respectively. They are very close to those obtained by Patriarche et al. (2007).

Role of water saturation

Two-phase flow simulations with TOUGH2/EOS7R help to further understand the variations in water saturation during gas migration and the possible effects on both permeability and porosity. Numerical simulations with both air and water flow often led to computational problems and premature stoppages. With an initial water saturation of 20%, water flow is almost nonexistent—but with a higher initial saturation of 80%, the tracer migrates more rapidly towards the surface, and the pressure increases in the chamber. The computed pressure was high compared to experimental data, which suggests that water saturation is lower or that dry fractures are acting as preferential flow paths.

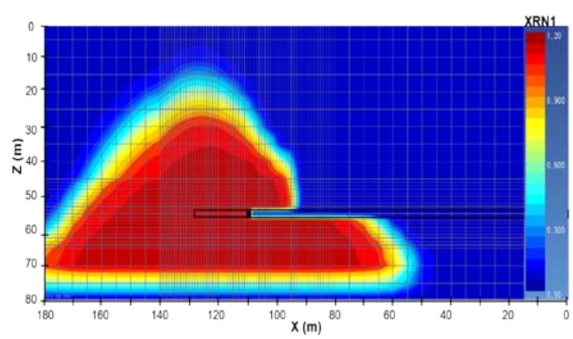

Figure 5. Fraction of the tracer (SF_6) in the gas phase after 60 h of air injection at 24 L/min in Chamber C obtained from numerical simulation with TOUGH2 /EOS7R.

CONCLUSION

An efficient and thorough determination of permeability in the field requires the acquisition of substantial data and interpretation of that data via numerical simulations. In the Roselend Natural Laboratory, permeability was investigated at the field scale, intermediate between borehole and regional scales. Preliminary simulations of two-phase flow confirmed that water saturation strongly influences gas migration in the unsaturated zone.

Further simulations using TOUGH2 will be conducted to improve our understanding of gas flow and transport between Chamber C and the surface. These simulations will also help in preparing and interpreting gas tracer experiments at Roselend.

We aim at modeling an atmospheric pressure boundary condition that would be variable over time. Pressure fluctuations in Chamber C, in response to barometric pressure fluctuations obtained from numerical simulations, could be compared to experimental data to give another estimation of permeability and porosity.

Future work includes introducing heterogeneity and fractures within the porous medium in order to investigate the effects of barometric pumping (Nilson et al., 1991) on gas migration in double porosity media.

ACKNOWLEDGMENT

We thank André Burnol from BRGM for introducing Sophie Guillon to numerical simulation with TOUGH2. The technical help of Patrick Carrera and Marc Perrier in the field is greatly appreciated. Thanks also to the city of Beaufort for granting access to the Roselend Natural Laboratory.

REFERENCES

Guillon S, Vu M.T., Pili E. and Adler P.M. Field and numerical determinations of air permeability of unsaturated fractured porous rocks on various scales. (in prep. for Water Resources Research)

Nilson, R. H., Peterson E. W., Lie K. H., Burkhard N. R. and Hearst J. R. Atmospheric pumping: a mechanism causing vertical transport of contaminated gases through fractured permeable media. *Journal of. Geophysical Research*, 96, 21933-21848, 1991.

Patriarche, D., Pili, E., Adler, P.M. and Thovert, J.-F. Stereological analysis of fractures in the Roselend tunnel and permeability determination. *Water Resources Research*, 43: 09421-09421, 2007.

Provost A.-S., Richon P., Pili E., Perrier, F., Bureau S., Fractured porous media under influence: the Roselend Experiment, *EOS Transactions, American Geophysical Union*, 85(12), 113-124, 2004.

Vu M.T., Applications of the level functions method in hydrogeology. Ph.D dissertation. Université Pierre et Marie Curie (Paris, France), 2012.

Wassermann J., Sabroux J. C., Pontreau S., Bondiguel S., Guillon S., Richon P., and Pili E. Characterization and monitoring of the excavation damaged zone in fractured gneisses of the Roselend tunnel, French Alps. *Tectonophysics* 503, 155-164, 2011.